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Risk Assessment of Aero Engine Failure Based on Monte Carlo Simulation

Hui CHEN, Longbiao LI ,Youchao SUN*

College of Civil Aviation, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, PR China

Abstract

The risk simulation model of aero engine failure has been developed based on Monte Carlo method. The model has been established to predict and evaluate the failure risk of aero engine during operational phase to ensure the reliability and security. Risk assessment of a particular engine was conducted on the basis of the failure events hazard level and the corresponding risk guidelines. During the assessment, three reasonable corrective actions have been developed and estimated to analyze the effect of different maintenance methods and inspectional intervals on the failure risk factor.

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Keywords: Aero engine, Risk assessment, Monte Carlo, Risk factor.

1. Introduction

With a growing demand of the global air transport, flight safety has become more and more important. Aero engine is the most critical parts of the flight safety and it also provides power for flight. But because of the improvement of the aero-engine performance and the increasingly complex structure of the aero-engine, the probability of failure of engine parts in-service would gradually increase. The failure of these critical parts can result in unsafe condition.

Currently, there are two main assessment methods for aero engine. The DARWIN [1] program integrated finite element stress analysis, fracture mechanics analysis, nondestructive inspection simulation, and probabilistic analysis to provide a probabilistic risk prediction and management tool for engine manufactures. Leverant [2] described several improvements to DARWIN program to ensure risk convergence and to further complete the program. These improvements including modify the further original finite element mesh, enhance the fracture mechanics capabilities, and in accordance with the

* Corresponding author. Tel.: +86-25-84895963.
E-mail address: sunyc@nuaa.edu.cn.

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impact of the failure probability to re-divided zones that had the same load, material properties and geometrical characteristics. However, the DARWIN program is mainly used for the assessment of discrete part zone. For risk assessment of engine failure events, especially large-scale, high technical difficulty and costly situation, risk assessment that based on the Monte Carlo simulation can effectively address these challenges. FAA published Advisory Circular AC39-8 [3], based on Weibull analysis and Monte Carlo simulation, and provides guidance and acceptable methods for assessing the risk of unsafe conditions on products associated with the Power-plant or Auxiliary Power Unit (APU) Installations on Transport Category Airplanes. Literature [4] introduces a simulation model of aero-engine failure risk with the application of Monte Carlo, and also analyzed the effects of the maintenance methods and the inspection intervals on the failure risk. Literature [5] was on the basis of AC39-8, introduces the method of the risk analysis and the analysis example of the eighth stage compressor disc fracture for a turbofan engine.

The research of the risk assessment of different engine failure is still in its infancy. Therefore, this paper is based on the Monte Carlo simulation and the risk guidelines to introduce a risk assessment method that suit for aero-engine operating phase. This method firstly based on Monte Carlo simulation to predict the number of the different unsafe condition or event, then according to the corresponding event hazard levels to calculate the risk factor and the risk per flight. Secondly, develop a variety of corrective actions to reduce the risk, and as well perform the Monte Carlo simulation on each action to assess the risk. Eventually, according to the risk guidelines to determine and implement the optimal action, so as to ensure that the risk of event of the operational phase of the aero-engine is always at a safe level.

2. The Definition of Risk Assessment

2.1. Hazard Level

The hazard level is the level of the engine event outcomes; it is defined by its effect on the aircraft, passengers and crew. Among all, the highest hazard level is Level 5 for catastrophic outcomes which would result in multiple fatalities, usually with the loss of the airplane. The next level is Level 4 which would result in such as forced landing, actual loss of aircraft, serious or fatal personal injuries and other serious consequences. And Level 3 would result in substantial damage to the aircraft or second unrelated system and other serious consequences. Because the lower severity of event of Level 2 and Level 1, this paper will not discuss them. And it is mainly for the event that is Level 3 or higher.

2.2. Hazard Ratio

The hazard ratio is the conditional probability that a particular aero-engine component failure mode will result in an event of a specific hazard level. And the hazard ratio converts the basic event risk factor to a risk factor for Levels 3, 4, and/or 5 events. It strongly influences the assessment results; therefore it should be assessed conservatively.

The hazard ratio is usually based on historical data. For instance, when at least one Level 3 or higher event has occurred, the hazard ratio for Level 3 or higher is the value obtained by dividing the number of Level 3 or higher events by the total number of events. However in reality, the probability of Level 3 or higher event is so low that no event has occurred and no historical data are available. For example, a fleet has four turbine failure events and all these events are Level 2 event. So the hazard ratio is 0/4=0 which is meaningless. It should make assumptions in this case which assume the next event would be Level 3 or higher, so that a conservative hazard ratio can be obtained. So assume the next turbine event is Level 3 event, then the hazard ratio can be 1/5 because 0:4 become 1:5.

2.3. Risk Guidelines

Risk factor refers to the average number of future engine event expected to occur in a given period of time, namely the frequency of risk events. The formula to calculate the risk factor is: Risk Factor = Expected Number of Event×Hazard Ratio. The purpose of calculating the risk factor is to be compared with the risk guidelines. Additionally, the risk factor should be converted to risk per flight to facilitate comparing risks on a common basis. Risk per flight refers to the risk of engine event of one aircraft during each flight, that is the probability of engine event occurred of one aircraft during each flight, and its value is equal to the risk factor multiplied by the engine total number divided by total engine flight number of cycles.

There are long-term and short-term guidelines for risk factor and the risk per flight. These guidelines are acceptable risk level for engine failure event, and also help to determine whether immediate action is necessary so that it can control the serious consequences of the risk. Table 1 lists Level 3 and 4 risk guidelines. For Level 5 events, there are currently no standardized guidelines available. This is due to that not enough experience has been accumulated on Level 5 events. In the interim, the Level 5 risk evaluation should always meet the Level 4 guidelines.

Table1. Risk Guidelines

	Level 3 Guidelines		Level 4 Guidelines	
	Risk factor	Per flight	Risk factor	Per flight
Long-term acceptable risk	——	1×10^{-8}	——	1×10^{-9}
Short-term acceptable risk	1.0	4×10^{-5}	0.1	4×10^{-6}

Uncorrected risk factor should be acceptable to long-term risk guidelines. If it exceeds the applicable Level 3 and Level 4 long-term risk guidelines, then it is a failure event and need corrective actions. While the short-term guidelines contain the risk factor and the risk per flight limiting values of Level 3 and 4 events. And corrected risk factor should be acceptable to short-term risk guidelines. Meanwhile if the risk of engine event exceeds the short-term guidelines within 60 days, immediate action should be considered. When a quantitative assessment of the risk is unavailable which is due to lack of data, the decision of whether immediate action is necessary should be made based on judgment and expert opinion.

3. The Risk Assessment Method of Aero-engine Failure

3.1. Monte Carlo Simulation of Aero-engine Failure

The Monte Carlo simulation is a random process which set repeatedly generated time series, calculated parameter estimators and statistics, and then study the distribution characteristics. Two-parameter Weibull distribution of failure function:

$$F(t) = 1 - \exp[-(t/\eta)^{\beta}] \tag{1}$$

where β and η are the shape parameter and scale parameter, the failure time is

$$t = \eta[-\ln(1 - \mathrm{F}(\mathrm{t})]^{1/\beta} \tag{2}$$

The following gives a step-by-step simulation procedure for engine failure event risk assessment, as shown in Figure 1.

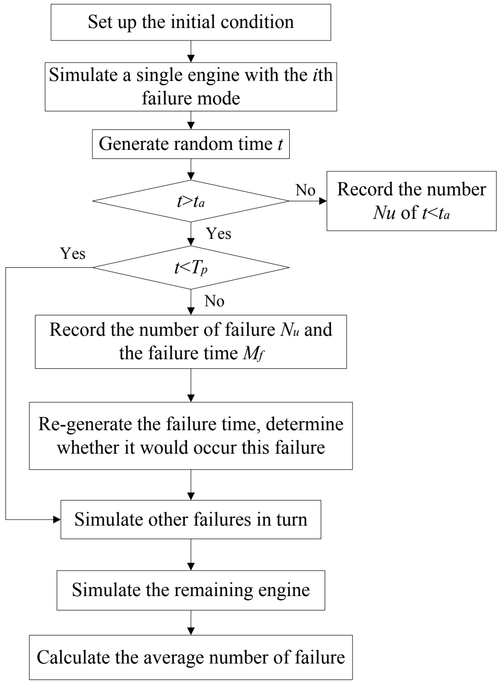

Fig.1. The Monte Carlo Simulation Process

Step 1. Set up the initial condition for the simulation. The following data is often required: the total number of engines m, the engine initial use time t_a, and maintenance cycles T_p, the utilization rate t_m, and the engine failure mode and their Weibull distribution shape parameter β and scale parameter η.

Step 2. Perform the simulation on a single engine first. It is assumed that the ith-failure mode of the engine occurs and then use the built-in rand function to generate random number which obeys (0, 1) uniformly distributed, N is the number of simulations. Next, use the Eq. (2) to generate the failure time t_i of this failure mode.

Step 3. If the engine has been used for t_a, compare it with the generated failure time t_i. If $t_a>T_p$, then make t_a equal the remainder number of t_a/T_p, record the number N_{ui} of $t_i<t_a$, selected the failure time t_i which is greater than t_a.

Step 4. Compare the failure time from Step 3 with the maintenance cycle. If $t_i>T_p$, then the engine has been maintained, and this failure mode does not occur. Otherwise, if $t_i<T_p$, this failure mode would occur. It needs to record the number of failures N_{fi} and the failure month M_{fi}.

$$M_{fi} = [(t_i - t_a) / t_m] + 1 \tag{3}$$

Step 5. Re-perform the simulation on this engine, Re-generates the random number F^c and the failure time t_i^c,and determine whether it would occur this failure mode. Afterwards calculate the total N_{ui}^d and N_{fi}^d of this engine. This program set the sampling frequency is 100 times. For the maintenance of service age, the stop sampling condition is $t_i^c>T_p$,and for the maintenance of Fixed interval is $t_i+t_i^c>T_p$.

Step 6. Step 2-5 for each different failure modes.

Step 7. Step 2-6 for each different engine. Calculate the total N_{ui}^s and N_{fi}^s of the total engine, as well as the number of the corresponding month of the occurrence of each failure mode.

Step 8. Calculate the failure rate and the average number of failure. The Equation of the failure rate of the i-failure mode of the sample in the k-month is

$$W_i = M_{fik} / (m + N_{ui} + N_{fi}) \tag{4}$$

The formula of the average number of failure is:

$$\overline{N_{fi}} = m \times W_i \tag{5}$$

And the average number of other failure mode can also be calculated by the same equation.

3.2. The Risk Assessment Procedure of Aero-Engine Failure

This risk assessment method is a systematic analysis method to assess the engine failure risk. It is based on the Monte Carlo simulation, the hazard ratios and the risk guidelines. The purpose of the assessment of the risk of engine failure is to determine whether an unsafe condition exists and then taking effective action to reduce the risk to an acceptable level, and then monitor the implementation of the action so as to ensure the flight safety.

The entire engine failure risk assessment process (shown in Figure 2). is as follows:

Step 1: Decide the hazard level of engine failure event. If the event is at least the Level 3 event then it needs to perform the risk assessment.

Step 2: Calculate the uncorrected risk factor, namely the risk factor before the implementation of the action. Perform the Monte Carlo simulation to predict the future failure risk that is calculating the number of the expected failure. And then risk factor is multiplied by hazard level to get the risk factor of Level 3 and Level 4 event, if they below the corresponding acceptable long-term risk guidelines, there is no need to continue the evaluation, otherwise, continue the evaluation according to the following steps.

Step 3: Develop a variety of candidate mitigating actions.

Step 4: Implement the appropriate mitigating action. The selection of actions and the determination of whether to implement the action should be based on the specific circumstances and the risk of failure events.

Step 5: Calculate the corrected risk factor, namely the risk factor after the implementation of the action. Translate the number of failure after the implementation of the action into Level 3 and Level 4 risk factor and risk per flight. Compare with the corresponding acceptable short-term risk guidelines to verify the effectiveness of the initial corrective actions. Generally, the initial actions may not be the complete response to the unsafe condition. Therefore, field experience and other data collected in the implementation of the action should be carefully audited to improve the effectiveness of the analysis and the risk assessment.

Step 6: Monitor the implementation of the corrective actions. Once it is practical, follow up the implementation of the action. Usually the initial action is not a complete response to the failure event, verification of any initial actions should not be feasible before the follow-up actions. The inspection results should continue to be monitored to ensure that any temporary actions continue to validate assumptions and projections. All actions assume that any factors that can lead to unsafe events are to eliminate.

Step 7: Follow-on assessments and responses. In many cases, the initial action for the failure event would not be sufficient to reduce the risk to an acceptable level, then follow-on responses and action may be required. The risk assessment process described above can be applied to the initial actions and the follow-on actions. The follow-on action may be complete understanding of the issues and influencing factors of unsafe condition. The initial action is based on limited or part of the data, and the follow-on action is usually based on more complete information. The purpose of the entire risk assessment is to remain the risk below the acceptable level.

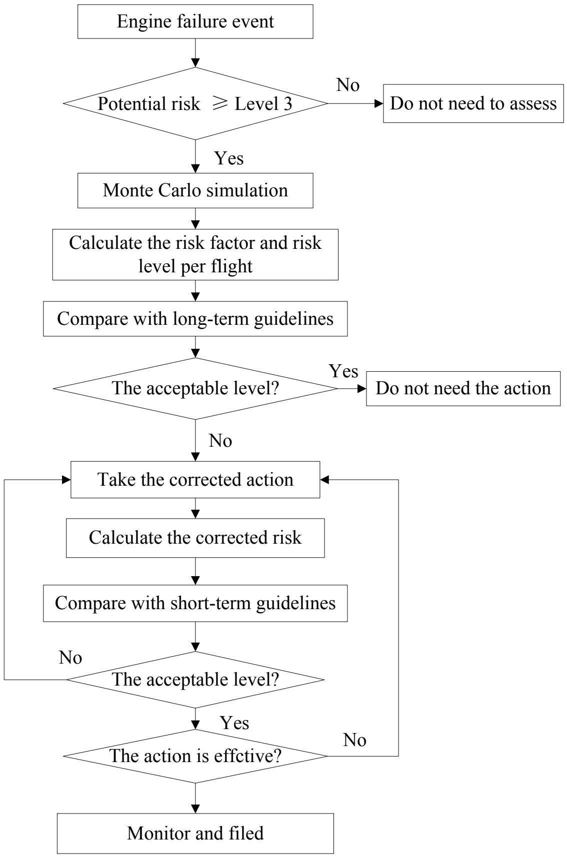

Fig. 2. The Risk Assessment Process of Engine Failure

4. The Real Case Of Engine Failure Assessment

4.1. Initial Data

The first step in aero engine risk assessment is to collect the historical failure data. These data will be used in the Weibull analysis and risk assessment. This paper statistics 1600 engine data, the utilization rate of engine t_m is 25h/month, maintenance cycle T_p is 1000h. And, through Weibull analysis, three kinds of distribution parameters of independent failure modes can be obtained, respectively for the turbine disk crack, compressor blades crack the tubing crack, see Table 2.

Table2. Weibull Distribution Parameters of Turbine Disk Crack, Compressor Blades Crack and Tubing Crack

	β	η(h)
turbine disk crack	2.09	10193
compressor blades crack	4.57	2336
tubing crack	1.89	12050

According to uncontained failure event history data summarized by FAA (see [6]), can respectively get the Level 3 and Level 4 hazard ratio C3, C4 of this three failure modes. For turbine disk crack, the Level 3 hazard ratio C3=3/21=0.14. For compressor blades crack, the failure event usually is Level 1 and 2 event, so the calculate of the hazard ratio should according to the 3.2, assuming the additional event would be Level 3, then the conservative calculations of the Level 3 hazard ratio C3=1/71=0.014. For tubing crack, the level of the failure event is low ,so the paper assume that they are all Level 2 event, assuming the additional event would be Level 3, then the conservative calculations of the Level 3 hazard ratio C3=1/501=0.002. Furthermore, this paper assume the life of the fleet is 20 years, and the total flight number is 1×10^9, so the original risk per flight is $1/(1\times10^9)= 1\times10^{-9}$. Due to the probability of the occurrence of the Level 4 event is very low, they are not discussed in this paper. Table 3 summarizes the risk factor of these three kinds of failure events and the corresponding formula.

Table3. Formula

	turbine disk	compressor blades	tubing
Hazard ratio of Level 3	0.14	0.014	0.002
Risk factor	Risk Factor = Expected Number of Event × Hazard Ratio		
Risk per flight	Risk per flight = Original Risk Per Flight × Risk Factor		

4.2. Initial Simulation Results

In the initial, perform Monte Carlo simulation without any further actions.

Therefore, perform the maintenance strategy of service age replacement, and make initial use time t_a= 0. According to the Monte Carlo simulation and the risk factor formula above to predict the risk of engine failure in 12-40 months, the results are shown in table 4.

Table 4. Result of Simulation and Calculation

	turbine disk	compressor blades	tubing
Predict number	11.903	34.188	15.832
Level3 risk factor	1.67	0.48	0.032
Level3 Risk per flight	1.67×10^{-9}	0.48×10^{-9}	0.32×10^{-10}

Compare the risk factor in Table 4 with the Table 1 long-term risk guidelines, the Level 3 and 4 risk factor of turbine disc is exceed the acceptable level, so the appropriate mitigating action is required. For compressor blades and tubing, there is no need to take any action because they are meet the acceptable level and the assessment should be called off.

4.3. Corrected Actions

Based on the trade-offs of various factors and resources, three optional corrected actions have been developed as follows:

Option A: Change the maintenance for fixed interval maintenance

Option B: Change the maintenance cycle， make T_p=800

Option C: Change the maintenance for fixed interval maintenance and the maintenance cycle for T_p=800

Re-perform the Monte Carlo simulation, and then calculate the risk factors and Risk per flight to assess the three actions, the results are list in Table 5.

Table5.Candidate actions and Effect for failure 1

options	A	B	C
Predict number	10.765	8.944	5.98
Level3 risk factor	1.51	1.25	0.83
Level3 Risk per flight	1.51×10-9	1.25×10-9	0.83×10-9

Compare the original risk factor with the risk factor from different optional action, as shown in Figure 3.The figure shows that all three optional actions can reduce the risk factor, but for option A and B, the Level 3 and 4 risk factors exceed the acceptable level of risk guideline, and therefore are not feasible. For option C, the Level 3 and 4 risk factors meet the short-term guidelines, that is the risk factor is 0.83<1 and the risk per flight is $0.83\times10^{-9}<4\times10^{-5}$. It is recommended to take C option to reduce the risk of the engine failure, and then monitor the implementation of the action. Based on the actual implementation of the action to determine whether to take the follow-on action or not.

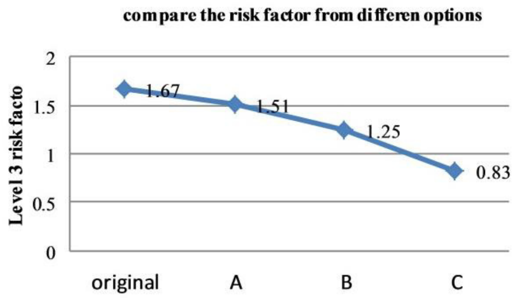

Fig. 3. Compare Risk Factor From Different Options

From the above engine failure risk assessment, it can be found that the change of maintenance cycle can significantly change the risk of failure, and the smaller the maintenance cycle, the smaller the failure risk. Additionally, the risk of fixed-interval maintenance is less than the maintenance of service age. This is because at fixed interval maintenance, regardless of the parts failure or not, it must be replaced, means that the fixed interval maintenance cycle is less than the maintenance of service age, so its failure risk is smaller. However, the cost of fixed interval maintenance is higher than service age maintenance, so in reality it should be integrated to trade-off a variety of factors to consider taking what maintenance strategy.

5. Conclusions

This paper describes how to perform the risk assessment for different engine failure event. The Monte Carlo simulation in this paper is very flexible. This simulation can be applied to the maintenance of both fixed interval and service age, and also applicable to the engine mitigating actions of different maintenance cycles, different utilization rate and so on. Therefore, the method described in this paper can be applied to other failure modes which may cause unsafe conditions, and it provides a relatively valuable reference for future engine failure risk assessment method.

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